Linear Spin-Valve Bridge Sensing Devices

Zhenghong Qian, Dexin Wang, Jim Daughton, Mark Tondra, Cathy Nordman and Anthony Popple

Abstract**—** Spin-valves are applied in a variety of devices including magnetic sensors and isolators. The linear spin-valve sensing element is configured as a Wheatstone bridge consisting of four sensing resistors. The sensing devices are characterized by three parameters: the sensing field range, sensitivity and linearity. The devices using linear spin-valve sensing elements exhibit excellent performance. A Linear magnetic field sensor constructed of a bridge with 4 μm wide line serpentine resistors shows a sensitivity of 1.6 mV/V-Oe in the operation range of –5 Oe to 5 Oe. An analog magnetic isolator constructed of a bridge with 4 μm wide line serpentine resistors exhibits superior performance with a sensitivity of 1.27 mV/V-mA and a linearity error less than 0.05%.

Index Terms**— Magnetics, Sensor, Isolator, Spin Valve, GMR**

I. Introduction

Spin valves have been extensively investigated and applied in a variety of linear device applications. These include, for example, magnetic read heads, magnetic field sensors and GMR (giant magnetoresistance) isolators [1-4]. The sensing element in the devices is commonly configured as a Wheatstone bridge consisting of four sensing resistors. The typical spin-valve resistor is made into the serpentine stripe, where the pinned layer is fixed in the transverse direction by exchange coupling with an antiferromagnetic layer (e.g. CrPtMn), and only the free layer is allowed to respond to the signal fields. The spin-valve sensing resistor offer significant advantages over other types of the sensing resistors, e.g. AMR (anisotropy magnetoresistance) sensing resistor and hall effect sensing resistors. The signal response of the spin-valve resistors is at least five times larger than the response of the AMR resistor in an equivalent field, leading to greater sensitivity, lower detection thresholds and simpler circuits. In addition, compared to the parabolic resistance change to a magnetic field for an AMR resistor, the linear spin-valve resistor is inherently linear if the hysteresis is suppressed. In this work, low hysteresis linear spin-valve sensing resistors were successfully prepared and utilized in magnetic devices including magnetic bridge sensors and analog isolators. The devices were evaluated with regard to the operation range, sensitivity and linearity.

Manuscript received October 15, 2003. The work is supported in part by DOD under F29601-02-C-0278 and NOAA under 50-DKNB-1-SB083.

All authors are with NVE Corporation, 11409 Valley View Road, Eden Prairie, MN 55344 (e-mail: zqian@nve.com).

II. Experimental

The spin-valve multilayers used in this work were deposited on Si/Si_3N_4(2kÅ) substrates. The serpentine sensing resistors were patterned using photolithography and Ar ion beam milling. The resistor stripe geometries are typically 2-6 μm wide lines and 2 μm spaces with taper-shaped ends. The size of resistor stripe is 40 μm x 70 μm. The resistance of the resistor is around 2.5 kΩ. For the design and fabrication detail of the sensing resistor, see reference [5]. Beside the sensing resistors, all other features and metal connection were defined by standard photolithography and wet/dry chemical etching techniques. The testing of the final devices were done with a test station.

III. Results and Discuss

A. Characterization of linear spin-valve resistor

The sensing element plays a key role in determining the device performance. Fig. 1 shows the MR loop of a 4 μm

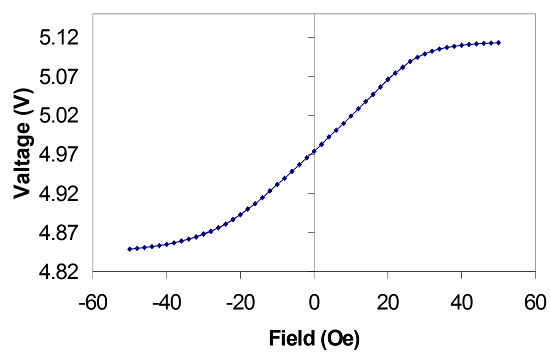


Fig. 1. GMR transfer curve of a 4 μm linear spin-valve serpentine resistor. The spin valve is with a configuration of Ta30Å-NiFeCo35Å-Ta40Å-NiFeCo42.5Å-CoFe12.5Å-Cu25Å-CoFe43.5Å-CrPtMn325Å.

spin-valve serpentine resistor measured with a constant current of 2mA. No visible hysteresis is observed and the linearity error is less than 0.05% in the operation range of –15 Oe to 15 Oe. The GMR is 5.43%, and the effective anisotropy H_k is ~ 29 Oe. Note the effective anisotropy is the mixed effect of the induced uniaxial anisotropy and shape anisotropy of the sensing layer. The calculated sensitivity is *Sensitivity* = GMR%/2Hk=5.43%/(2*29)=0.094%/Oe. The characteristics of the sensing resistor are very useful in predicting the device performance. Theoretically, the sensing range and sensitivity

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **15 OCT 2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**

4. TITLE AND SUBTITLE **Linear Spin-Valve Bridge Sensing Devices**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **NVE Corporation,11409 Valley View Road,Eden Prairie,MN,55344-3617**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

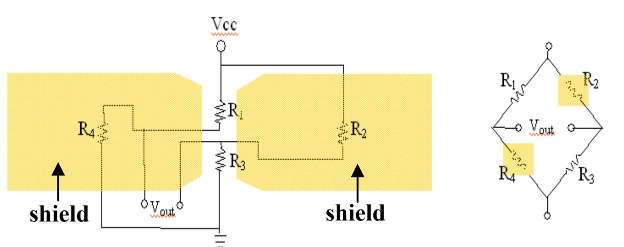
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**3**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

of the device can be calculated from the effective anisotropy H_k of the free layer as well as the shields and/or flux concentrators applied. The H_k is determined by three factors: the relative orientation of the easy axis of the sensing layer, the thickness of the sensing layer and the resistor linewidth. The H_k decreases as the resistor linewidth increases. As a comparison of a H_k of 29 Oe with a 4 µm linewidth, the H_k is 62.8 Oe with a 2 µm linewidth, 40.4 Oe with a 3 µm linewidth and 20.5 Oe with a 6 µm linewidth. Since the GMR changes very little with the change of the resistor linewidth, the sensitivity increases with an increase of the resistor linewidth. Another importance device parameter is the linearity error, which is mainly due to the hysteresis of the sensing layer. In order to reduce/eliminate the hysteresis, several detrimental effects need to be minimized. The first one is the Barkhausen Noise, which is mainly due to the creation and annihilation of domain walls during the magnetization reversal of the sensing layer. The second one is the fringe field from the pinned layer, which is highly nonuniform and can affect the magnetization reversal of the free layer and cause a degradation of linearity, The third one is the dispersion of the free layer. If these detrimental effects are eliminated, the linear spin-valve sensing resistor is inherently linear. In this work, the spin valve is employed with double free layers as noted in Fig. 1, which can effectively reduce the influence of the fringe field from the pinned layer and help to adjust the bias point of the sensing resistor [5].

B. Linear Bridge Field Sensor

Fig. 2 shows the sensor arranged in a Wheatstone bridge



(a) (b)

Fig. 2. Bridge sensor with flux concentrators: a)sensor configuration and b)Wheatstone bridge connection.

configuration. Two resistors (R_2 and R_4) are shielded by NiFe thick layers (~10 µm) while the other two sensing resistors (R_1 and R_3) are not shielded and open to the external signal field. Each shield is 280 µm x 224 µm in size and the gap between the shields is 65 µm wide. The shields can not only shield the influence of the external field on the shielded resistors but also serve as the magnetic flux concentrators to magnify the external filed on the unshielded resistors. The flux concentrators increase the field seen by the resistors in the gap by a factor approximately equal to the length divided by the gap width. The bridge output reflects the resistance change of the two unshielded sensing resistors. Fig. 3 shows the response of the bridge output to the signal field.

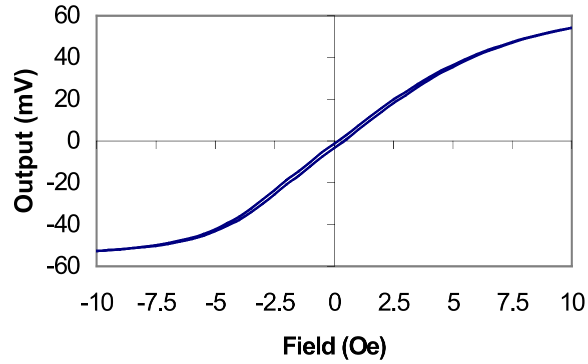


Fig. 3. The response of the bridge output to the signal field. Note the bridge is with a 5 volts power supply (Vcc = 5 V).

The sensor operation range is –5 Oe to 5 Oe. The sensitivity of the sensor to the signal field is 1.6 mV/V-Oe. This value is high due to the effect of the flux concentrators, which increase the field in the gap by approximately a factor of four. However, the sensor also exhibits an obvious hysteresis and poor linearity. As discovered in the finished devices, the hysteresis is mainly due to the shields (or the flux concentrators), which exhibit poor characteristics including large hysteresis and nonlinearly. The signal field magnified and distorted by the shields lead to the degradation of the sensor linearity. In order to improve the linearity of the sensor, two measures could be used. One is to reduce/eliminate the hysteresis in the shields; the other one is to use the electronic compensation as shown in Fig. 4.

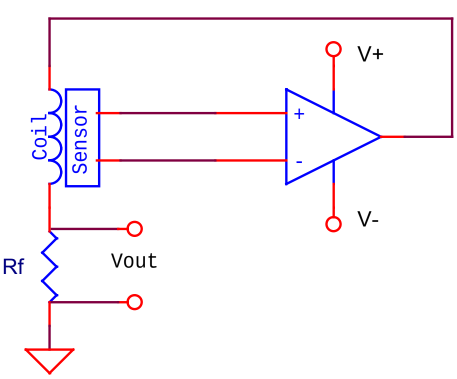


Fig. 4. Closed-loop magnetic field sensor.

The compensated close-loop magnetic sensor consists of a magnetic sensor, an amplifier and a feedback coil. The sensor output voltage is first amplified, and the amplifier's output current then flows through a feedback coil to generate a magnetic field whose amplitude is the same but whose direction is opposite to the measured field. The output current converts to a proportional output voltage by placing a feedback resistor R_f in series with the coil. This magnetic feedback can improve the linearity as well as the dynamic range of the sensor. However, the on-chip feedback coil will greatly increase the power dissipation and process complexity.

C. *Analog isolator*

In this work, linear spin-valve sensing bridges were also successfully incorporated into analog isolators. Fig. 5 shows

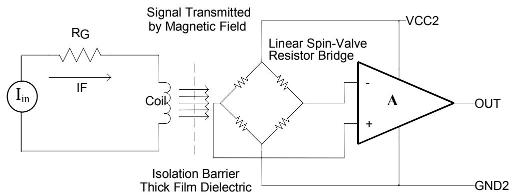


Fig. 5. Schematic of GMR analog isolator.

the simplified schematic of a magnetoresistance analog isolator. The functionality of the GMR isolator is similar to the optocoupler but operates with a different principle. A forward signal current through the on-chip coil generates a magnetic field signal, which is then transmitted and detected by the spin-valve sensing bridge on the other side of the isolation barrier. Fig.6 shows a linear spin- valve analog isolator test cell.

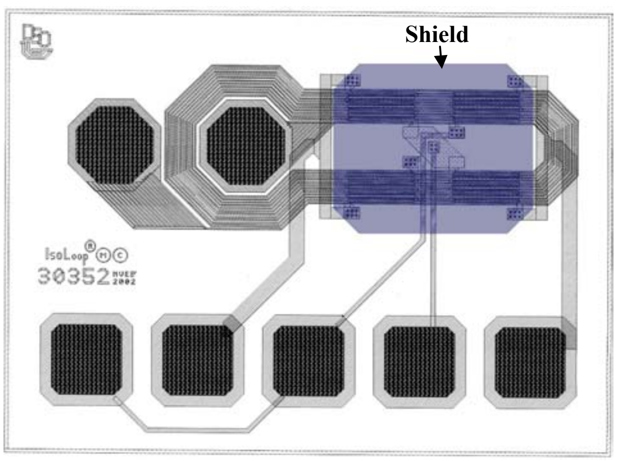


Fig. 6. An Analog isolator layout.

The spin-valve sensing resistors are laid below the coil. The sensitive axis is perpendicular to the coil turns. A soft magnetic permalloy shield is laid above the coil and the serpentine resistor structures. The shield attenuates external fields while serving as a flux concentrator to the on-chip field improving coil efficiency. In the finished device, The spin valve resistors are physically isolated from the coil by an 12 μm BCB isolation barrier, which is capable of providing an isolation breakdown voltage larger than 2000V**.** The shield is ~ 10 μm thick, and the coil efficiency is ~ 1.5 Oe/mA. Note the coil efficiency is the ratio of the magnetic field generated on the spin-valve sensing element to the current passing through the coil. The device shows excellent performance. Fig. 7 is the isolated bridge output to the sweeping signal current through the on-chip coil in a fully processed analog isolator. The response exhibits a negligible hysteresis with a small bridge offset of ~ 2 mV. The full range of operation is from –20mA to 20 mA (Fig. 7a). The linearity error is less than 0.05% in the range of –10 mA to 10mA, where the response is virtually a straight line as shown in Fig. 7b. The sensitivity is 1.27 mV/V-mA.

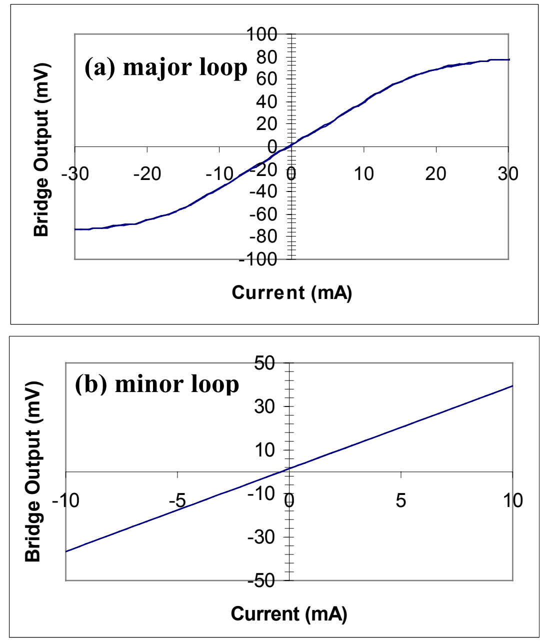


Fig. 7. Isolated bridge output to the signal current sweep in a fully processed analog isolator.

IV. Conclusion

Linear spin-valve resistors have been successfully prepared and applied in linear magnetic field sensors and analog isolators. The devices were evaluated with regard to the operation range, sensitivity and linearity. The sensors show a high sensitivity of 1.6 mV/V-Oe but with a poor linearity due to the effects of the poor shields, and the solutions for improving the sensor performance are proposed. The isolators exhibit excellent performance with a linearity error less than 0.05% in the operation range of –10 mA to 10 mA.

References

[1] J. M. Daughton, "GMR applications", J. Magn. Magn. Mater., vol. 192, pp. 334-342, 1999.

[2] C. Tsang, R. Fontana, T. Lin, D. Heim, V. Speriosu, B. Gurney, and M. Williams, "Design, Fabrication and Testing of Spin-Valve Read Heads for High Density Recording," IEEE Trans. Magn. Vol. 30, pp. 3801-3806, 1994.

[3] D. Heim, R. Fontana, C. Tsang, V. Speriosu, B. Gurney, and M. Williams, "Design and Operation of Spin Valve Sensors," IEEE Trans. Magn. Vol. 30, pp. 316-321, 1994.

[4] Z. Qian, D. Wang, J. Daughton, M. Tondra, E. Lange, C. Nordman, T. Popple, J. Myers and J. Schuetz, "Magnetic Signal Isolators Employing Linear Spin-Valve Sensing Resistors", J. Appl. Phys., 93, 6870-6872(2003).

[5] Z. Qian, J. Daughton, D. Wang, M. Tondra, "Magnetic Design and Fabrication of Linear Spin-Valve Sensors", IEEE Trans. Magn. Vol. 39, pp. 3322-3324, 2003.